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Analysis of scenarios for the reduction of energy consumption and GHG emissions in transport in the Basque Country

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ABSTRACT

Fossil energy depletion and fight against climate change force humanity to decarbonize the economy. By year 2050 CO_2 emissions will have to reduce globally at least 85%, and probably over 95% in developed countries.

The modeling of the transportation of people and commodities in the Basque Autonomous Community (Spain) in year 2008 has allowed us to draw some conclusions about the challenges ahead. The exploration of several scenarios modeled in order to reduce energy consumption in transport shows that mobility in a decarbonized world will have to be more efficient, electrified when moving people and freight on land, based on renewable generation, and organized in such a way that guarantees very high occupancies of vehicles. All these elements will be indispensable, and even not sufficient if they are still not complemented with a reduction of mobility in absolute terms, so that economic transportation intensity—the ratio between transportation and whole economic activity—recovers to levels seen in the world four decades ago, prior to the development of present hypermobility.

Contents

1. Introduction

Humanity is facing an enormous double threat that inevitably compels us to consume much less energy. The International Energy Agency (IEA) has recently asserted that global crude oil output probably reached its all-time peak of 70 Mb/d in 2006 [1], as currently producing oilfields show a declining rate of almost 6% per year that can be hardly offset with new capacity [2]. On the other hand, the International Community has acknowledged that, in order to avoid a catastrophic climate change of unexpected consequences, it is essential to hold the increase in global temperature below 2 °C [3]. Scientific research suggests that a target for the stabilization of atmospheric CO_2 should be set not over 350 ppm [4]. A detailed analysis of the emission trajectories for stabilization developed by the IPCC in its 4th Report [5] allows to conclude that humanity is forced to reduce CO_2 emissions by 85% by 2050, and developed countries by 95%. As 61.4% of world oil production is consumed in the transport sector [6]—oil accounts for 93.5% of

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the energy consumed worldwide for transportation—, the consequences imposed by energy scarcity and climate change mitigation will be enormous in that sector. It is urgent to reduce energy consumption in transportation; but which are the options offered by technology and urban management in order to reach such ambitious figures, and their respective potential reductions?

A number of recent publications have tried to answer these questions from the perspective of specific countries and specific transport sub-sectors. For example, Ashina et al. [7] propose a roadmap to achieve an 80% reduction in CO_2 emissions in Japan by 2050, with a reduction between 74% and 94% in the transport sector. But prospects are very dependent on policy and socio-economic conditions. Another study from Thailand [8] concludes that fuel switching and highly energy efficient cars would mitigate emissions in that country by just 3.3% by 2030 when compared to a reference scenario, in which the transport sector would more than triple 2008 consumption levels. In Malaysia, Ong et al. [9] identify an emissions reduction potential for road transport of almost 13% when a combination of mitigation strategies—shift to public transport and natural gas, vehicle renewal—is applied to just 10% of transport demand in 2007. For the road transport sector in China, according to Ou et al. [10] the use of alternative vehicles and fuels could allow to reduce greenhouse gas (GHG) emissions by 27.6% by 2050; Huo et al. [11] increase that figure up to 42%, and another work [12] gives a 39.9% reduction by 2030 with a combination of efficiency, technology and policy measures. All studies for China, however, consider reference scenarios in which energy demand form road transport will more than quintuple by 2050.

For Canada, Steenhof et al. [13] state that using hydrogen and electric vehicles for passenger transportation, combined with a decarbonized electricity grid, could decrease total CO_2 equivalent emissions by 31% in 2050 when compared to a reference scenario, although still maintaining emissions 6% above 2005 levels.

In the European Union (EU), Mattila and Antikainen [14] have identified technological options for reducing GHG emissions in long distance freight transport by 80%, mainly by improving vehicle and engine efficiency, and using alternative fuels. Pasaoglu et al. [15] consider that passenger road transport emissions in EU-27 can decrease by 35–57% when compared to 2010 levels, with a combination of alternative fuels, technological improvements, deployment of hybrids, battery-electric, plug-in hybrid and fuel cell vehicles, decarbonization of electricity and a hydrogen mix.

Another interesting reference about the potentials for energy consumption and emissions reductions, in this case worldwide, is the Energy [R]evolution 2010 outlook report from Teske et al. [16], in which they try to demonstrate the feasibility of reducing energy demand by 15% in the transport sector from 2007 to 2050, while increasing the renewable energy share from a low 2% in 2007 up to almost 70% by 2050. This work assumes increased use of public transport, a faster uptake of efficient combustion and electric vehicles, and less vehicle use and important lifestyle changes.

1.1. Analysis of scenarios in the Basque Autonomous Community

This work will examine several options offered by technology and urban management in order to reduce energy consumption and emissions, and their respective potential reductions, referring to the case of the transport sector in the Basque Autonomous Community (BAC), in the north of Spain.

The BAC, as a region of an EU member (Spain), is absolutely conditioned by European policies. Recently, the European Council has reconfirmed the EU objective of reducing GHG emissions by 80–95% by 2050 compared to 1990 levels [17]. The European Commission has also approved a Roadmap to a Single European Transport Area [18], with initiatives aimed at achieving a 60% GHG emission reduction in transport by the middle of the century. These initiatives would imply the phase out of conventionally fueled cars in urban transport by that time, and a significant reduction of oil imports.

These plans ought to be implemented at national levels. The use of biofuels and the decrease in mobility are addressed, for example, as effective measures to slightly reduce CO_2 emissions in the metropolitan area of Madrid (capital of Spain) in the very short term [19]. Another study [20] identifies a potential for a 70% reduction of the emissions in the Spanish transport sector by 2020 with respect to a reference scenario, and 50% below 2004 levels. Sadly, current policies in Spain are not that ambitious. The Action Plan on Energy Efficiency and Energy Savings [21], approved by the Spanish Government in July 2011, sets the objective to reduce energy consumption in transportation by 19.9% in 2020, when compared to a reference scenario, but still assuming that more energy would be consumed in transport in that year than in 2004 (1.1% more).

Unfortunately, the regional Government of the Basque Country in not much more ambitious than the Spanish. In its recently approved Energy Strategy for 2020 [22], it sets the aim to reach a share of oil-alternative fuels—renewable electricity, biofuels—in road transport of just 15% in 2020, and of 40% in 2030.

This work will explore six different medium-term scenarios for deep energy consumption reductions in the transport sector in the BAC, based on the available data provided by local administrations for year 2008, and based on five particular options—the sixth scenario is a combination of all examined options—which, although ambitious, could be achievable, based on recently published state-of-the-art studies. In particular, this work will explore the consumption reductions offered by: a vigorous effort in efficiency during the next decade; a massive electrification of land transport vehicles; supply of electricity from renewable energy sources; a strong commitment to public transportation of people; an important reduction of transport intensity as a consequence of relocalization of the economy; and a combination of all previous factors.

2. Transport in the Basque Autonomous Community in 2008

With a surface of 7534 km^2 and a population of 2.1 million inhabitants, the population density in the BAC (283 p/km^2) is among the highest ones in the EU [23]. The BAC is made up of three provinces—Bizkaia, Araba and Gipuzkoa—with a high competence level for fiscal issues, infrastructure management and transport policies. The economy of the BAC is completely integrated with the Spanish, and presents a very important import/export exchange with the rest of the EU and other nations, based on a very dense communications and transportation network with surrounding territories, not only by road and railway, but also by means of its three airports—one in each province—and its two commercial seaports—in both maritime provinces, Bizkaia and Gipuzkoa. The urban landscape of the BAC is often described as a polynuclear system of cities, in which the capitals of the Basque provinces sum up two thirds of the total population, and the other third is quite evenly distributed among smaller and hierarchically dependent towns and villages. This territorial design gives way to a territorial organization in which each of the provinces is further subdivided into *comarcas*, each with several small towns.

Annual transport statistics allow to characterize with high detail the transportation of freight and people throughout the territory. In particular, our work is based on the data provided for year 2008 by OTEUS, the Observatory for Transport of the BAC, dependent on the Basque Government [24]. The data provided by that report has been complemented with other data provided by the Basque Energy Agency (EVE), also dependent on the Basque Government, altogether with other data from specific companies of the transport

sector—metro, railway and others [25,26]. In order to know how is energy consumed in the transport sector in the Basque Country we have crossed available data both for transportation demand and energy consumption for year 2008 in the BAC. Quite alarmingly, this process has uncovered some serious deficiencies related to transport and energy statistics in the BAC.

In general, the energy consumption of vehicles can be calculated by (1) when they transport people:

$$E_f[\mathrm{MJ}] = \mathrm{People}\,[\mathrm{person}] \times \mathrm{Journey}\,[\mathrm{km}] \times \frac{\mathrm{Fuel\ Economy}\,[\mathrm{MJ/km}]}{\mathrm{Vehicle\ Capacity}\,[\mathrm{person}] \times \mathrm{Occupancy}[\%]} \quad (1)$$

And by (2) when they transport commodities:

$$E_f[\mathrm{MJ}] = \mathrm{Freight}\,[\mathrm{t}] \times \mathrm{Journey}\,[\mathrm{km}] \times \frac{\mathrm{Fuel\ Economy}\,[\mathrm{MJ/km}]}{\mathrm{Vehicle\ Capacity}\,[\mathrm{t}] \times \mathrm{Loading}\,[\%]} \quad (2)$$

This way, the calculation of energy consumption in transport demands knowing not only what travels and how far, but also vehicle consumption, which in turn depends on vehicle capacity and loading.

Left aside for a moment vehicle consumption data, the first amazing fact about transportation information in the BAC is that it is commonly reported in a way that makes it impossible to directly derive any accurate consumption estimation. Most of the transportation data is reported just as *passengers* [p] or *tonnes of freight* [t], without any reference to the distance traveled. Fortunately, the movement of people is usually classified by the length of the journey—intracomarcal, interprovincial, and so on—, and in the case of freight movement some information is often available about destinations. Based on it, a detailed accounting of people and freight transportation has been carried out in this work for different modes and classified according to length of journey, making educated guesses for the average journey length where necessary. Results are gathered in Table 1.

With respect to vehicle consumption, data have been obtained from different sources [25,27,28], but mainly from Harvey [29], which gathers abundant information about the energy consumption of a wide variety of vehicles, form cars and trucks to airplanes, with different propulsion technologies. Vehicle consumption data can be provided in two ways. One is by means of the fuel consumption per kilometer, measured in MJ/km—commonly known as *fuel economy*. Once vehicle capacity and its loading are known, fuel economy can be converted into the *energy intensity of transport*, measured in terms of MJ/p km or MJ/t km. The other possibility is to characterize vehicle consumption directly measured in MJ/p km or MJ/t km, as happens when characterizing mass-transportation vehicles such as trains, ships or airplanes. These data generally assume specific capacity and loading coefficients, which may have to be corrected for the cases under study. In our case, all the data, sources and assumptions are reflected in Table 1.

Our energy model calculates not only the consumption of final energy in the transport sector, but also the primary energy required to supply that final energy. Following Harvey [29], our model considers a Primary Energy/Final Energy ratio of 1.2 for all fuels except electricity, for which a ratio of 2.13 has been used, based on the information provided by the IEA [30] in its 2008 energy balances for Spain. Our model also calculates GHG emissions associated to primary energy consumption. For oil products 73.5 g CO_2e/MJ are considered; that factor is doubled for aviation consumption in order to reflect a much higher radiative forcing of emissions in high altitudes [31]; and a factor of 108.3 g CO_2e/MJ is used for electricity, based on emission levels in the Spanish electric system—390 g CO_2/kWh in 2008 [32].

In order to check out the correctness of the assumptions made, total energy consumption given by our model has been compared with other aggregate data provided by the Basque Energy Agency for year 2008 [33]. Similar data are available for GHG emissions [34]. This comparison has uncovered some faults in energy accountancy related to transport in the Basque Country.

First, there is no specific calculation of energy consumption in the reports published by the organizations dependent on the Transport Department of the Basque Government. Every energy data is directly taken from the reports published by the EVE, but some serious faults arise in those reports: strictly following EU's methodology for the accounting of energy consumption and GHG emissions, the Basque administration does not take into account energy consumption and emissions from international shipping and aviation [35]. In energy balances, final energy consumption never includes the item of international marine bunkers, which although reflecting international shipping, in energy accountability appears always subtracting in the calculation of Total Primary Energy Supply (TPES). But this methodological—and quite questionable—rule must be corrected when accounting aggregate consumption data in the transport sector—when accounting the energy balance for the world as a whole, the IEA includes international marine and aviation bunkers in final consumption of the transport sector [36]. Secondly, something similar occurs with GHG emissions data related to international aviation, too, as these concepts are not covered by the Kyoto Protocol. But this lack of consistency cannot give way to a dishonest underestimate of energy consumption and GHG emissions. To avoid these faults, our model has been checked against the energy and emissions data taking into account these methodological differences, as our model does consider international shipping and aviation with origin or destination in our region as part of the Basque transport sector. For non-local transport of any mode, journeys accountable for the Basque transport sector are considered to be half of the total, as we consider that the other half should be charged to the destination territory.

Data provided by our model for energy consumption and GHG emissions in the transport sector of the BAC are gathered in Table 1. People and freight movement, energy consumption and GHG emissions are itemized and classified by passenger or freight transportation, transport modes, journey, propulsion technology and fuel. The set of exact values provided by our model should be taken just as an approximation to the real—and probably inaccessible—ones, and the significance of our model does not lie on its accuracy, but on the fact that their parameterization allows to track the changes in aggregate energy consumption when specific changes are applied to the ways in which people and freight are moved in our country. These changes and their implications will by analyzed in the next section.

Although the exact values from Table 1 should be taken with prudence, nevertheless they let us make some general considerations about how was energy consumed in 2008 in the transport sector in the BAC. Some aggregate data is shown in Figs. 1–4.

While local administrations account that in 2008 energy consumption in the transport sector was 1905.5 ktoe, our model indicates that real consumption could be up to a third larger. Similarly, GHG emissions given by our model are 42% larger than those provided by the administration (5705 kt CO_2), although it must be pointed out that around a 20% increase should be charged to the fact that we have estimated GHG emissions from primary energy data—considering, for example, that the consumption of 1 kg of gasoline requires an additional 0.2 kg of gasoline-equivalent to be consumed upstream the energy chain.

Moreover, the transport sector in the BAC presents characteristics quite similar to those of other OECD countries: One third of consumption corresponds to freight transport; an insignificant part of the energy consumed is of renewable origin, being the rest crude

Table 1a
Data related to transport of people in the BAC for year 2008.

Transport mode & vehicle	Journey	Private/ public transport	Technology & fuel	Passengers (millions)	Average distance (km)	Transport (million p km)	Vehicle capacity (passengers)	Loading (%)	Fuel economy (MJ/km)	Energy intensity (MJ/p km)	Final energy (ktoe)	Primary/final energy ratio	Primary energy (ktoe)	GHG emissions (g CO_2e/MJ)	GHG emissions (t CO_2e)
Road/Cars & Light Trucks	Intracomarcal	Private	SI-ICE/Gasoline	249.4[a]	5[b]	1247	4	30.5%[e]	2.12[f]	1.73	51.48	1.2[f]	61.78	73.5[f]	158.92
			CI-ICE/Diesel	1413.1[a]	5[b]	7066	4	30.5%[e]	1.92[f]	1.57	264.49	1.2[f]	317.38	73.5[f]	816.47
	Intercomarcal & Intraprovincial		SI-ICE/Gasoline	67.2[a]	40[b]	2686	4	30.5%[e]	2.12[f]	1.73	110.90	1.2[f]	133.08	73.5[f]	342.35
			CI-ICE/Diesel	380.5[a]	40[b]	15,221	4	30.5%[e]	1.92[f]	1.57	569.76	1.2[f]	683.72	73.5[f]	1758.86
	Interprovincial		SI-ICE/Gasoline	9.9[a]	80[b]	790	4	30.5%[e]	2.12[f]	1.73	32.60	1.2[f]	39.13	73.5[f]	100.65
			CI-ICE/Diesel	55.9[a]	80[b]	4475	4	30.5%[e]	1.92[f]	1.57	167.51	1.2[f]	201.01	73.5[f]	517.10
	National		SI-ICE/Gasoline	6.9[a]	175[b]	1205	4	30.5%[e]	2.12[f]	1.73	49.77	1.2[f]	59.72	73.5[f]	153.64
			CI-ICE/Diesel	39.0[a]	175[b]	6831	4	30.5%[e]	1.92[f]	1.57	255.69	1.2[f]	306.83	73.5[f]	789.33
Road/Bus & Coach	Intracomarcal	Public	CI-ICE/Diesel	66.7[a]	5[b]	333	85	20%[e]	19.25[b]	1.13	8.98	1.2[f]	10.78	73.5[f]	27.74
	Intercomarcal & Intraprovincial			47.7[a]	40[b]	1909	55	20%[e]	12.25[b]	1.11	50.62	1.2[f]	60.75	73.5[f]	156.27
Rail/Metro	Intracomarcal		Electric motor/Electricity	86.3	6.33	546.4[c]	550[c]	23%[c]	46.96[c]	0.37[c]	4.85	1.025[f]	4.97	0.0[f]	0.00
Rail/Tram (EuskoTran)	Intercomarcal		Electric motor/Electricity	2.96[a]	2.71	8.0[b]	192[d]	20%[b]	23.50[f]	0.61	0.12	2.13[h]	0.38	108.3[b]	0.53
Rail/Train (RENFE)			Electric motor/Electricity	25.79[a]	30[b]	773.6	300[b]	30%[b]	180.00	0.60[f]	11.05	2.13[h]	23.55	108.3[b]	50.28
Rail/Train (FEVE)			Diesel-electric/Diesel	1.51[a]	15[b]	22.6	300[b]	30%[b]	420.00	1.40[f]	0.75	1.2[f]	0.90	73.5[f]	2.32
Rail/Train (EuskoTren)			Electric motor/Electricity	17.94[a]	10[b]	179.4	300[b]	30%[b]	180.00	0.60[f]	2.56	2.13[h]	5.46	108.3[b]	11.66
Air/Airplane	National		Turbojet/Kerosene	3.5[a]	244[a]	853.1	125	70%[b]	357.14	2.86[f]	58.04	1.2[f]	69.64	147.0[f]	358.31
	International		Turbojet/Kerosene	1.1[a]	400[a]	440	125	70%[b]	357.14	2.86[f]	29.93	1.2[f]	35.92	147.0[f]	184.80
Seaborne/Ship			Diesel-electric/Fuel-oil	1.80[a]	500[a]	89.8		80%[b]		1.25[g]	2.67	1.2[f]	3.21	73.5[f]	8.25

SI: Spark Ignition; CI: Compression Ignition; ICE: Internal Combustion Engine.

[a] Source: [24].
[b] Educated guess.
[c] Source: [25].
[d] Source: [26].
[e] Source: [28].
[f] Source: [29].
[g] Source: [27].
[h] Source: [30].

Table 1b
Data related to transport of freight in the BAC for year 2008.

Transport mode & vehicle	Journey	Technology & fuel	Passengers (millions)	Average distance (km)	Transport (million t km)	Vehicle capacity (t)	Loading (%)	Fuel economy (MJ/km)	Energy intensity (MJ/t km)	Final energy (ktoe)	Primary/final energy ratio	Primary energy (ktoe)	GHG emissions (g CO_2e/MJ)	GHG emissions (t CO_2e)
Road/Cars & Light Trucks	Intracomarcal – Intramunicipal	CI-ICE/Diesel	17.64[a]	10[b]	176.4	5	85%[b]	6.38	1.50[c]	6.30	1.2[c]	7.56	73.5[c]	19.45
	Intercomarcal – Intermunicipal	CI-ICE/Diesel	59,182[a]	50[b]	2959	5	85%[b]	5.53	1.30[c]	91.59	1.2[c]	109.91	73.5[c]	282.74
Road/Heavy Trucks	National – Origin in BAC	CI-ICE/Diesel	26,063[a]	156[a]	4054	28	85%[b]	17.85	0.75[c]	72.40	1.2[c]	86.88	73.5[c]	223.50
	National – Destination in BAC	CI-ICE/Diesel	24,410[a]	156[a]	3797	28	85%[b]	17.85	0.75[c]	67.81	1.2[c]	81.37	73.5[c]	209.33
	International – Origin in BAC	CI-ICE/Diesel	2620[a]	500[b]	1310	28	85%[b]	16.66	0.70[c]	21.83	1.2[c]	26.20	73.5[c]	67.40
	International – Destination in BAC	CI-ICE/Diesel	3208[a]	500[b]	1604	28	85%[b]	16.66	0.70[c]	26.73	1.2[c]	32.08	73.5[c]	82.53
Rail/Train (RENFE)	Intercomarcal	Electric motor/Electricity	4379.2[a]	47.5[b]	208.1		85%[b]		0.30[c]	1.49	2.13[d]	3.17	108.3[b]	6.76
Rail/Train (FEVE)	Intercomarcal	Diesel-electric/Diesel	1053.6[a]	133.6[b]	140.8		65%[b]		0.50[c]	1.68	1.2[c]	2.01	73.5[c]	5.17
Rail/Train (EuskoTren)	Intercomarcal	Electric motor/Electricity	183.3[a]	39.2[b]	7185.4		85%[b]		0.30[c]	0.05	2.13[d]	0.11	108.3[b]	0.23
Air/Airplane	National	Turbojet/Kerosene	11,087[a]	200[b]	2.22				15.00[c]	0.79	1.2[c]	0.95	147.0[c]	4.89
	International	Turbojet/Kerosene	27,145[a]	1045[b]	28.35				15.00[c]	10.13	1.2[c]	12.15	147.0[c]	62.52
Seaborne/Ship	International – Unloadings	Diesel-electric/Fuel-oil	30,969[a]	2137[b]	66,189				0.25[c]	393.98	1.2[c]	472.78	73.5[c]	1216.22
	International – Loadings	Diesel-electric/Fuel-oil	11,737[a]	2137[b]	25,086				0.25[c]	149.32	1.2[c]	179.19	73.5[c]	460.96
	National – Local traffic	Diesel-electric/Fuel-oil	1265[a]	60[b]	75,912				0.47[c]	0.85	1.2[c]	1.02	73.5[c]	2.62
	National – Provisioning	Diesel-electric/Fuel-oil	192.7[a]	100[b]	19.27				0.25[c]	0.11	1.2[c]	0.14	73.5[c]	0.35
	National – Fishing	Diesel-electric/Fuel-oil	7.7[a]	500[b]	3850				0.47[c]	0.04	1.2[c]	0.05	73.5[c]	0.13

SI: Spark Ignition; CI: Compression Ignition; ICE: Internal Combustion Engine.

[a] Source: [24].

[b] Educated guess.

[c] Source: [29].

[d] Source: [30].

oil derivates; just over one tenth of people transportation is public transit; and almost one half (45%) of all transport crosses regional borders—national (Spanish) and international transport.

Regarding freight transport, heavy trucks in the BAC deliver much of the merchandize that in other countries is carried by train. The preponderance of ship transport is mainly due to the fact that more than half of the freight received in the commercial port of Bilbao corresponds to LNG and oil products that feed a regasification terminal and Petronor, one of the biggest refineries in Spain. With respect to transportation of people, private vehicles are dominant. A significant part of that transit, though, corresponds to local journeys.

3. Future scenarios in the transport sector aimed at reducing energy consumption

Our model allows us to explore future scenarios, based on the parameterization of the consumption calculated following formulas (1) and (2). This work has explored five different scenarios:

1. Efficient Scenario. Following present trends in efficiency and without any ground-breaking innovation, significant reductions in consumption are achieved in less than two decades. Although this scenario implies important improvements in technology and would require investment budgets to renew transport infrastructure, it is supposed to be feasible and a good reference for the near future.
2. Electrification Scenario. Massive electrification of cars and railway vehicles is achieved, with all other vehicles corresponding to the Efficient Scenario. This scenario gives us some clues about the potential of a massive use of electricity in transport, and would imply major changes in electricity demand and distribution, a profound renewal of private vehicles, and should force us to rearrange our mobility habits, as electric vehicles offer in general, due to the limited energy density of batteries, much more limited ranges than other propulsion technologies.

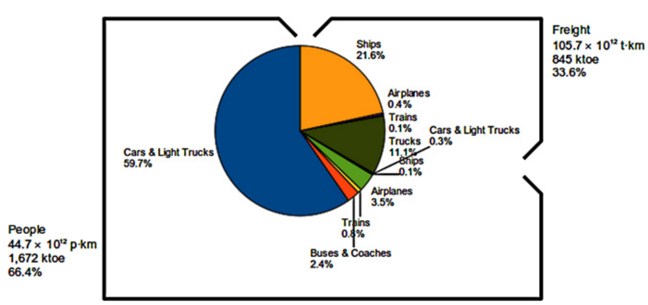

Fig. 1. Breakdown by transport mode of final energy consumption in transport in 2008.

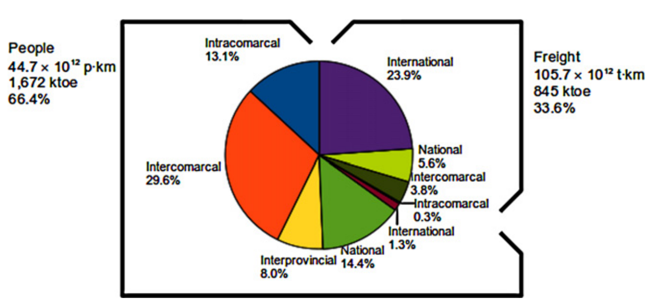

Fig. 2. Breakdown by journey of final energy consumption in transport in 2008.

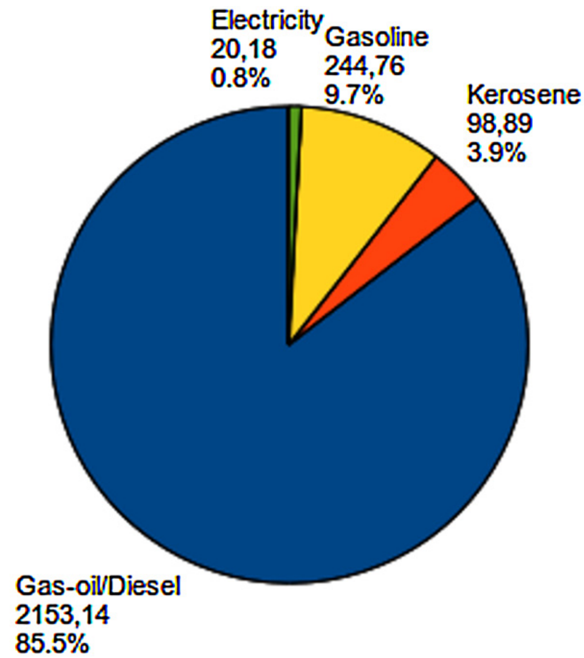

Fig. 3. Breakdown (% and ktoe) of different energy carriers in final energy consumption of transport in 2008.

3. Electrification & Renewables Scenario. Like the previous, but all the electricity consumed in transport is generated from renewable energy fluxes.
4. Public Transport Scenario. As shown in Table 1 and Figs. 1 and 4, private vehicles with quite low occupancies account for almost 90% of final energy consumed when moving people, and more than half of all energy consumption in transport. In this scenario a profound transformation for the transportation of people is envisaged. By means of it, energy consumption is reduced and homogenized in terms of MJ/p km throughout all transport modes of people on land, due mainly to the increase of vehicle occupancy.
5. Relocalization Scenario. In our globalized world transportation is highly linked to economic activity. Nevertheless, as will be shown later economic and transport activities have increased at quite different rates during the last decades, and actually many administrations state a firm decision to decouple economic growth from increases in transport. In this scenario the transport intensity of the economy recovers the levels seen in

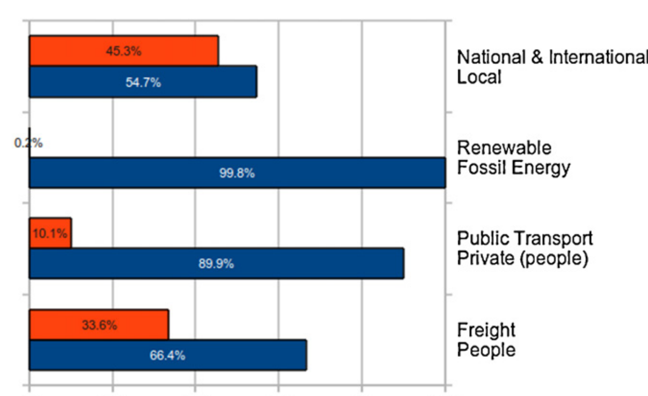

Fig. 4. Breakdown of final energy consumption in transport in 2008, classified by several general criteria.

Spain forty years ago, when hypermobility [37] was not as spread as today.

The scenarios explored in this work do not precisely define any desired target to be reached in the near future. Actually, as will be seen, many characteristics of each scenario remain open and undefined, as remain highly unknown the transition paths—in some cases quite revolutionary—that should be followed by economic agents, administrations and society in general. As we are convinced that climate change mitigation and energy scarcity—this last one especially in the Basque Country, with an external dependence of 95% of TPES—will set a major burden to transport in the near future, we will focus on the energetic implications of the assumptions made in each scenario; and our main concern will be the technological viability of every condition assumed. Most of the technological paths and possible evolutions assumed in this work have been taken from Harvey [29] and references given in that text.

3.1. Efficient Scenario

In this scenario significant reductions in energy consumption are achieved in less than two decades, thanks to efficiency improvements that may follow present trends (see Table 2).

In the future air transportation will continue to be the most energetically intensive, although improvements in efficiency, reductions in airplane weight and others may reduce energy intensity up to 10% from 2008 through 2020.

Although ship propulsion is already quite efficient, in seaborne transportation a 24% reduction of energy intensity is achievable from 2008 through 2020 if speeds are systematically reduced by 10% (from Harvey [29]; and coherent with [38], recently published).

With respect to rail transport, the Efficient Scenario assumes that trains with internal combustion engines (ICE) could reduce their energy intensity by 20% due to improvements in diesel engines, while electric trains—which already present quite high efficiencies—would reduce energy consumption by just 5%, down to energy intensities only clearly beaten by ship transport.

Road transport with big vehicles—heavy trucks for freight, buses and coaches for people—could withstand a significant 53% reduction on energy intensity thanks to a series of improvements all over the energy chain involving a variety of factors such as aerodynamics, engine and transmission technology, speed reductions and others. This reduction in consumption is important, but not that much if compared with the 35% reduction that is expected for 2020 in some business-as-usual scenarios (BAU).

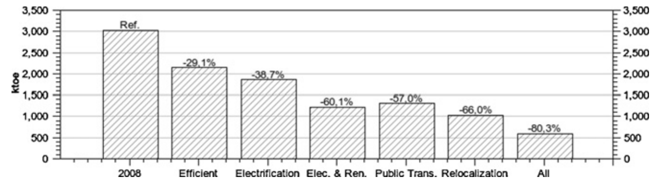

Fig. 5. Primary energy consumption in transport for the analyzed scenarios.

In respect to road transport by car, our model has assumed, based on the literature and forcing aggregate results to match with data given by local administrations, that in 2008 the average fuel economy of cars in the BAC was circa 2.0 MJ/km, or 6.6 L/100 km for gasoline engines (spark ignition ICE) and 5.5 L/100 km for diesel engines (compression ignition ICE). While in a BAU scenario fuel economy should be reduced down to 1.5 MJ/km by 2020, our Efficient Scenario supposes a more intense reduction of 30.5% down to 1.39 MJ/km by means of increasing engine and transmission efficiency, and reducing loads.

But ICE cars are not the only option nowadays. Hybrid electric vehicles (HEV) show fuel economies slightly better than ICE cars, and are expected to be reduced by almost a half by 2020. Electric vehicles will be probably used in their plug-in hybrid version (PHEV), with a fuel economy of 0.5 MJ/km when running on electricity, and 1.5 MJ/km when running on gasoline. Global fuel economy should be very dependent on the range desired for the vehicle, as the range on electricity will continue to be limited by battery capacity. As a high penetration of electric vehicles should carry with it important changes not only in electric infrastructure but also in mobility habits due to reduced ranges of electric vehicles, the Efficient Scenario will suppose that private electric vehicles remain being marginal, and that all road transport is supported by very efficient cars with advanced ICE engines.

This way, important reductions could be reached in the Efficient Scenario for both energy consumption and GHG emissions. As shown in Figs. 5–9, supposed that transportation demand is not changed, both primary and final energy consumption in the transport sector in the BAC would be reduced a little over 29% when

Table 2
Energy consumption parameters for each transport mode in the Reference Scenario (2008) and in the Efficient Scenario.

Transport mode	2008	2020 trend	Efficient Scenario
Internal Combustion Engine (ICE)	2.0 MJ/km (2.2 MJ/km in 2000)	1.5 MJ/km	1.39 MJ/km 30.5% reduction from 2008
Hybrid Electric Vehicle (HEV)	1.8 MJ/km (2.0 MJ/km in 2000)		0.97 MJ/km
Plug-in Hybrid Electric Vehicle (PHEV)			1.50 MJ/km (gasoline) 0.50 MJ/km (electric)
Bus/Coach (ICE)	1.1 MJ/p km	0.73 MJ/p km 35% reduction	0.53 MJ/p km 53% reduction
Heavy Truck (ICE)	0.70–0.75 MJ/t km	0.46–0.49 MJ/t km 35% reduction	0.33–0.35 MJ/t km 53% reduction
Train with ICE	1.40 MJ/p km 0.50 MJ/t km		1.12 MJ/p km 0.40 MJ/t km 20% reduction due to improvements in Diesel engines
Electric Train	0.6 MJ/p km 0.3 MJ/t km		0.57 MJ/p km 0.28 MJ/t km 5% reduction
Ship (ICE)	1.25 MJ/p km 0.25–0.47 MJ/t km		0.95 MJ/p km 0.19–0.36 MJ/t km 24% reduction for 2008–2020 (37% 2000–2020)
Airplane (Turboprop)	2.86 MJ/p km 15.00 MJ/t km		2.57 MJ/p km 13.50 MJ/t km 10% reduction for 2008–2020 (20–25% for 1995–2030)

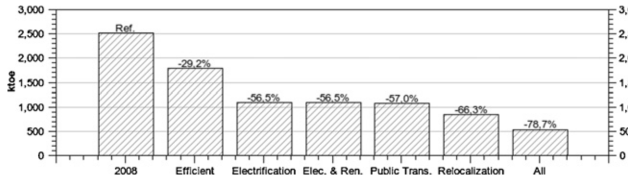

Fig. 6. Final energy consumption in transport for the analyzed scenarios.

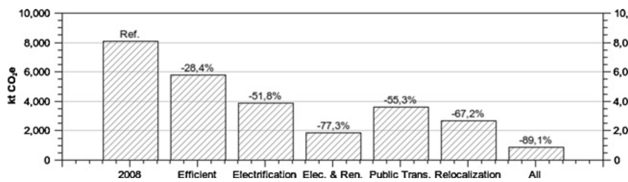

Fig. 7. GHG emissions related to transport for the analyzed scenarios.

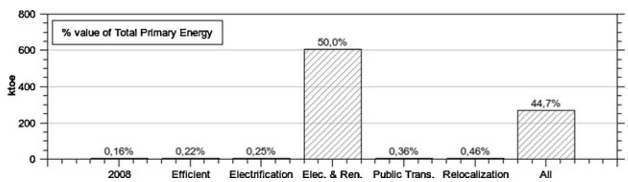

Fig. 8. Contribution of renewable energy to primary supply for transport in the analyzed scenarios.

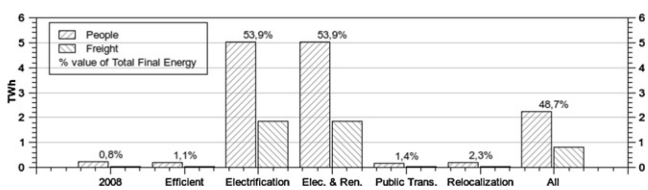

Fig. 9. Electricity consumption in transport for the analyzed scenarios.

compared to consumption in year 2008. That in turn would imply a 28.4% reduction of GHG emissions.

3.2. Electrification Scenario

This scenario explores the reduction margin for energy consumption in the transport sector if every movement of people and freight on land were made with electrified vehicles. Our assumptions for road transport in this scenario are that all cars and small trucks are electric and have an energy economy of 0.5 MJ/km. Heavy trucks and buses would not reduce energy intensity when compared to the Efficient Scenario, although all energy consumed in vehicles would be in the form of electricity. All rail transport would be converted into electric, which shows lower energy costs. Air and sea transport characteristics would be those of the Efficient Scenario.

Under these conditions our model suggests that final energy consumption could be reduced by 56.5% when compared to the Reference Scenario (2008), or an additional 27% if compared to the Efficient Scenario. The reduction would be mainly due to the fact that electric vehicles are significantly more efficient than those with ICEs. But electricity has to be generated and provided to vehicles from other primary energy carriers, so energy consumption has to be also checked in a primary energy basis. In that case, the reduction of primary energy demand is less significant: 38.7% when compared to the Reference Scenario, and just 9.6% below that in the Efficient Scenario.

GHG emissions would be also significantly reduced, almost 52% when compared with 2008. Although emissions levels in the Spanish electric grid are nowadays higher than those from the combustion of oil derived fuels—108 g CO_2/MJ and 74 g CO_2/MJ, respectively, when compared in a final energy basis—, more efficient electric motors would allow a net reduction of emissions. Besides, in this scenario only a fraction of electricity would come from the exploitation of renewable energy fluxes. Although almost a third of all generation into the Spanish electric system is nowadays of renewable origin, renewable generation in the BAC is close to marginal—generation is mainly based on natural gas combined cycles—and our model has left a strong development of renewable electricity for another scenario.

This way, the electrification of land transport would imply that almost 54% of all final energy consumed would be electricity: 5 TWh/year for the transportation of people, and 1.9 TWh/year for freight transport. As a reference, the final consumption of electricity in the BAC in 2008 was 16.29 TWh[1]; so this scenario of profound electrification would demand for an equivalent of more than 40% of the electricity consumed in all other sectors.

The much higher demand of electricity expected in this Electrification Scenario would have to be previously generated and distributed. This would obviously demand new infrastructures and investments in the electric sector, but not only there. All ICE vehicles would have to be renewed to electric propulsion, which would require a deep reconversion of the whole automotive industry. At last but not least, massive electrification of private vehicles on road would demand behavioral changes, as cars would have shorter ranges and would need much longer battery-refilling times.

3.3. Electrification & Renewables Scenario

This scenario is an evolution of the previous one, in which all the electricity is generated from renewable energy fluxes. In this case final energy consumption would not change, but the use of renewable sources would further reduce primary energy consumption, as energy chains that provide electricity from renewable fluxes are much shorter and thus more efficient than those based on fossil fuels. Primary energy demand would be 60% less than in the Reference Scenario, and 31% less than in the Efficient Scenario (Table 3).

Under these circumstances just half of primary energy consumed for transport would be electricity of renewable energy; and its generation would be a major challenge, but not impossible. According to Ekman [39], 2.5 out of 2.8 million cars in Denmark could be electric vehicles and fed from wind energy following a vehicle-to-grid scheme by year 2050. In the Basque Country, if the almost 7 TWh needed annually to feed electric transport were to be generated by wind farms or solar photovoltaic (PV) systems, 3.5 GW of wind capacity—assuming an annual productivity of 2000 h—or 4.7 GW of PV systems—supposing a productivity of 1500 h annually—would be required somewhere. These magnitudes contrast with the forecasts and plans of the Basque Government [22] for wind energy, which in its most optimistic scenario would increase from present 155 MW up to 1.4 GW in 2020. And 2.5 GW of PV systems, with an energy density of 50 W/m^2, would demand 5000 hectares of land, or a tenth of all already artificialized land in the BAC in 2008 (50,000 ha).

3.4. Public Transport Scenario

The main element of this scenario is a strong commitment to public transportation of people. Promotion of public transport is classically acknowledged as a quite straight way to reduce energy consumption in transport, as energy intensity of mass transit tends

[1] A nuclear plant with 1 GW of power and a capacity factor of 85% generates 7.5 TWh per year.

Table 3
Energy consumption parameters for each transport mode in the Electrification Scenario.

Transport mode	2008	Electrification Scenario
Internal Combustion Engine (ICE)	2.0 MJ/km (2.2 MJ/km in 2000)	Not used
Hybrid Electric Vehicle (HEV)	1.8 MJ/km (2.0 MJ/km in 2000)	Not used
Plug-in Hybrid Electric Vehicle (PHEV)		1.50 MJ/km on gasoline 0.50 MJ/km on electricity
Bus/Coach (ICE)	1.1 MJ/p km	0.53 MJ/p km (Efficient Scenario, but all electricity) 53% reduction
Heavy Truck (ICE)	0.70–0.75 MJ/t km	0.33–0.35 MJ/t km (Efficient Scenario, but all electricity)53% reduction
Train with ICE	1.40 MJ/p km 0.50 MJ/t km	Not used
Electric Train	0.6 MJ/p km 0.3 MJ/t km	0.57 MJ/p km 0.28 MJ/t km 5% reduction (Efficient Scenario)
Ship (ICE)	0.25–0.47 MJ/t km	0.16 MJ/t km (Efficient Scenario) 0.30 MJ/t km
Airplane (Turboprop)	2.86 MJ/p km 15.00 MJ/t km	2.57 MJ/p km (Efficient Scenario) 13.50 MJ/t km

Table 4
Energy consumption parameters for each transport mode in the Electrification Scenario (energy consumption in terms of MJ/km is maintained for each transport mode in both scenarios).

Transport mode	2008 Scenario		Public Transport Scenario	
	Loading	Energy intensity	Loading	Energy intensity
Cars (ICE)	30.5%	1.14 MJ/p km	85%	0.41 MJ/p km
Bus & Coach	20%	0.53 MJ/p km	30%	0.35 MJ/p km
Metro	23%	0.35 MJ/p km	23%	0.35 MJ/p km
Tram	20%	0.89 MJ/p km	45%	0.40 MJ/p km
Train	30%	0.57–1.12 MJ/p km	45–65%	0.38–0.52 MJ/p km

to be lower than that of private cars. But as can be seen in Table 4, where energy consumption parameters for each transport mode on land in the Reference (2008) and the Public Transport Scenarios are compared, it is possible to reduce energy intensity just by means of increasing the occupancy of vehicles; actually, a fully loaded efficient car could even consume less energy per passenger and kilometer than a bus or a train with the average loading (30–40%). Therefore, the increase of loading factors of small vehicles is as important as the change from private small vehicles to bigger ones. This would imply a massive use of carsharing and carpooling schemes.

Down to which level could be reduced energy intensity using these strategies? In our Public Transport Scenario it will be supposed that all transport modes have converged to a very similar energy intensity, mainly by readjusting the average occupancy factors in vehicles in each transport mode. The chosen value has been 0.4 MJ/p km, in the range assumed by Gilbert and Perl [27] for future transport and local public transport in China and the USA in year 2025. As shown in Table 4, this would imply an increase of the average loading factor of cars from 30.5% in 2008 up to 85% in the future. Loading factors should be also slightly increased in other transport modes. The singularity of this scenario is that if all modes converge to a similar energy intensity, possible changes from one transport mode to another would not change aggregate data of energy consumption, which greatly simplifies its calculation.

This way, if all road transport modes for people converge to an energy intensity of 0.4 MJ/p km, independently of how is transport organized and assuming that this would entail almost a full loading of small road vehicles with ICE engines, then both primary and final energy could decrease 57% when compared to that of the Reference Scenario. This rearrangement of transport would also allow to reduce GHG emissions 55.3%.

3.5. Relocalization Scenario

Although transportation is highly linked to economic throughput, economic and transport activities have increased at quite different rates during the last decades. Table 5 shows the different evolution of transport of people and freight in Spain and in the European Union from 1970 until 2008 [40]. While inflation adjusted GDP has doubled in Spain for that period [41], transport in general has increased much more: Freight transportation has multiplied by 4.1 in the same period; land transport of people by 4.2; and marine freight transport at world level has multiplied by 3.1.

In this scenario the economic transportation intensity is assumed to recover the levels seen in Spain forty years ago, when hypermobility was not as spread as today. This way, the Relocalization Scenario supposes that economic activity of the Reference Scenario (2008) is maintained, but with the economic transportation intensity of 1970. As road transport, for example, has multiplied by 4.6 in that period, but the economy has only doubled, road transport should be corrected by a factor $f = 2/4.6$; or reduced by 57%. Applying the same rule, seaborne transport should be reduced in this scenario by 35%. For air transport there is no available data; but as air transport will probably be one of the first victims of oil depletion in an energy constrained world, a 90% reduction has been assumed.

With these assumptions, final and primary energy consumption and related GHG emissions could be reduced by two thirds (66–67%).

3.6. Scenario with all options exploited in order to reduce GHG emissions and energy consumption

In this last scenario, all previous options for reducing energy consumption in the transport sector are combined. This scenario assumes that following present trends, and without groundbreaking technological innovations, all propulsion technologies improve efficiencies with reductions in fuel economy that range from 5% for electric trains up to 53% for heavy trucks and buses with diesel motors. Presence of ICE engines in road vehicles, though, would be minimal in this scenario, as road transport would be completely electrified. This would allow for important reductions in final energy consumption, as electric vehicles would be more efficient (0.5 MJ/km for cars) than the most efficient ICE vehicles. In this scenario electricity would come completely from

Table 5
Evolution of transport of people and freight in Spain and in the European Union between 1970 and 2008.

Transport mode	Unit	Spain			European Union		
		1970	2008	2008/1970	1970	2008	2008/1970
Railway	10^6 t km	10.3	10.3	×1.0	507.6	426.7	×0.8
Road	10^6 t km	51.7	238.7	×4.6	396.2	1699.5	×4.3
Pipeline	10^6 t km	1.0	9.1	×9.1	80.3	120.1	×1.5
Freight—Total	10^6 t km	63.1	258.1	×4.1	1095.2	2389.1	×2.2
Railway	10^9 p km	15.0	24.0	×1.6	301.3	407.5	×1.4
Car	10^9 p km	64.3	339.1	×5.3	1458.2	4392.8	×3.0
Bus & Coach	10^9 p km	20.9	60.9	×2.9	337.9	500.9	×1.5
Road	10^9 p km	85.3	400.0	×4.7	1796.1	4893.7	×2.7
People—Total	10^9 p km	100.2	424.0	×4.2	2097.4	5301.1	×2.5

Transport mode	Unit	World			GDP change (inflation adjusted)	
		1970	2008	2008/1970		
Freight—Seaborne	10^9 t miles	10,441.2	32,352.9	×3.1	EU	×2.7
					Spain	×2.0

renewable energy sources, reducing even more the dependence on fossil fuels commonly used in electric generation (natural gas, coal) and helping to reduce GHG emissions. Important reductions in energy consumption would be achieved, also, by a massive conversion of people movement on land from private small cars to public transport. In this last case, reaching complete occupancies of cars by carpooling and carsharing schemes would be also a viable way to reduce energy intensity down to a convergence value of 0.4 MJ/p km for all modes on land. Finally, this scenario supposes that the economy would undergo a relocalization process by means of which economic transportation intensity would return to the values seen in Spain forty years ago, with a socioeconomic situation prior to the globalization processes suffered in the world during the last two decades. This would imply reducing road transport by 57%, sea transport by 35% and air transport by 90%.

Under these circumstances consumption of final energy in the transport sector could be reduced by 78% when compared to consumption in the BAC in that sector in 2008. The supply of primary energy for transport could be reduced by more than 80%, and GHG emissions would be reduced by 89%. Electricity from renewable sources would sum up to almost a half of all final energy consumed in transport, or 3 TWh of electricity.

3.7. Some words about biofuels

The reader has probably noted that our scenarios have not considered the possibility to substitute liquid fuels of fossil origin (diesel, gasoline, kerosene) with biofuels obtained from biomass. In principle, our position is that the exploitation of biofuels on a large scale using sustainable schemes is more than disputable due to their very low energy return on energy invested (EROEI) [42]. Nevertheless, if we assume that it is possible to obtain biofuels sustainably with a net productivity of one tonne equivalent of oil per hectare annually (1 toe/ha year)—complete sustainability is quite difficult to check, if not impossible in the case of biomass, but that value seems to be a good reference [43]—, taken into account that diesel and kerosene demand in the last scenario would be 276 ktoe—compared to 2487 ktoe in the Reference Scenario—, the complete substitution of fossil liquids with biofuels would demand a land surface of 2760 km^2 to be dedicated to the production of biofuels for transport. If we consider that the BAC has a surface of 7534 km^2, it should be clear that only a small fraction of the final demand of fuels could we substituted with the local production of biofuels. Oil depletion will force society to consume much less liquid fuels in transport, and sustainability will probably call for even farther reductions if these fuels have to be derived from biomass.

4. Conclusions

The analysis of the previous scenarios allows to draw some general conclusions about the viable ways that society may take to reduce energy consumption in the transport sector. Although our analysis is based on the specific conditions of the Basque Autonomous Community, many ideas can be generalized.

Fossil energy depletion and climate change mitigation will force society to reduce fossil energy consumption in such a proportion—no less than 85%, and probably closer to 95% by year 2050—that every option to reduce consumption will be absolutely indispensable. There is no “silver bullet” of technological nature capable of reducing energy consumption as much as needed. Improvements in efficiency could provide reductions of almost a third of total final energy, but that is not enough. Complete electrification of land transport could reduce primary energy demand for transport between 40% and 60%, depending on the fraction of renewable energy; in a 100% renewable scenario GHG emissions could be cut by almost 80%, but that would ask for a 40% increase in the final demand of electricity in the whole economy.

But there are other routes not so linked to changes in propulsion technology and energy carriers. The first one would be, in road transport, to do without the use of cars with very low occupancies, in favor of other transport modes with much lower energy intensities—being these mass transit or just personal vehicles with high occupancies. The potential reductions to be reached by this route could be comparable to those brought by electrification. And finally, the straightest route to reduce energy consumption in transport would be to reduce the demand for transport in the economy. Taken into account that ours is the society of hypermobility, a reduction of the economic transportation intensity down to the values correspondent to the socioeconomic climate in Southern Europe four decades ago would allow to double the reductions provided by efficiency improvements. If this important reduction in transport demand were complemented with the previous routes, then required reductions of energy consumption and GHG emissions might be reached. But this would ask for a thorough transformation of modern civilization in which not only engineers working in propulsion technologies and renewable generation should be involved, but also city planners, economists, policy makers and society as a whole.

References

[1] International Energy Agency. World energy outlook 2010; 2010.
[2] International Energy Agency. World energy outlook 2008; 2008.

[3] UNFCCC. Copenhagen accord; 2009 [accessed June 2011] http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.
[4] Hansen J, Sato Mki, Kharecha P, Beerling D, Berner R, Masson-Delmotte V, et al. Target atmospheric CO_2: where should humanity aim? Open Atmos Sci J 2008;2:217–31, doi:10.2174/1874282300802010217.
[5] Intergovernmental Panel on Climate Change. Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge/New York: Cambridge University Press; 2007.
[6] International Energy Agency. Key World energy statistics 2010; 2010 [accessed June 2011] http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf.
[7] Ashina S, Fujino J, Masui T, Ehara T, Hibino G. A roadmap towards a low-carbon society in Japan using backcasting methodology: feasible pathways for achieving an 80% reduction in CO_2 emissions by 2050. Energy Policy 2011, doi:10.1016/j.enpol.2011.11.020. ISSN 0301-4215.
[8] Pongthanaisawan J, Sorapipatana C. Greenhouse gas emissions from Thailand's transport sector: trends and mitigation options. Applied Energy 2011, doi:10.1016/j.apenergy.2011.09.026. ISSN 0306-2619.
[9] Ong HC, Mahlia TMI, Masjuki HH. A review on emissions and mitigation strategies for road transport in Malaysia. Renewable and Sustainable Energy Reviews 2011, October;15(8):3516–22, doi:10.1016/j.rser.2011.05.006. ISSN 1364-0321.
[10] Ou X, Zhang X, Chang S. Scenario analysis on alternative fuel/vehicle for China's future road transport: life-cycle energy demand and GHG emissions. Energy Policy 2010, August;38(8):3943–56, doi:10.1016/j.enpol.2010.03.018. ISSN 0301-4215.
[11] Huo H, Wang M, Zhang X, He K, Gong H, Jiang K, et al. Projection of energy use and greenhouse gas emissions by motor vehicles in China: policy options and impacts. Energy Policy 2011, doi:10.1016/j.enpol.2011.09.065. ISSN 0301-4215.
[12] Yan X, Crookes RJ. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Policy 2009, February;37(2):658–68, doi:10.1016/j.enpol.2008.10.008. ISSN 0301-4215.
[13] Steenhof PA, McInnis BC. A comparison of alternative technologies to de-carbonize Canada's passenger transportation sector. Technological Forecasting and Social Change 2008, October;75(8):1260–78, doi:10.1016/j.techfore.2008.02.009. ISSN 0040-1625.
[14] Mattila T, Antikainen R. Backcasting sustainable freight transport systems for Europe in 2050. Energy Policy 2011, March;39(3):1241–8, doi:10.1016/j.enpol.2010.11.051. ISSN 0301-4215.
[15] Pasaoglu G, Honselaar M, Thiel C. Potential vehicle fleet CO_2 reductions and cost implications for various vehicle technology deployment scenarios in Europe. Energy Policy 2012, January;40:404–21, doi:10.1016/j.enpol.2011.10.025. ISSN 0301-4215.
[16] Teske S, Pregger T, Simon S, Naegler T, Graus W, et al. Energy [R]evolution 2010—a sustainable world energy outlook. Energy Efficiency 2011;4:409–33, doi:10.1007/s12053-010-9098-y.
[17] European Commission. A Roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; 2011.
[18] European Commission. WHITE PAPER Roadmap to a Single European Transport Area—towards a competitive and resource efficient transport system, COM(2011) 144 final; 2011 [accessed December 2011] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:EN:PDF.
[19] Lumbreras J, Valdés M, Borge R, Rodríguez ME. Assessment of vehicle emissions projections in Madrid (Spain) from 2004 to 2012 considering several control strategies. Transportation Research Part A: Policy and Practice 2008, May;42(4):646–58, doi:10.1016/j.tra.2008.01.026. ISSN 0965-8564.
[20] Pérez Martínez PJ. Consumo de energía por el transporte en España y tendencias de emisión. Observatorio Medioambiental 2008;11:127–47. ISSN 1139-1987 http://revistas.ucm.es/index.php/OBMD/article/view/OBMD0808110127A/21296.
[21] Government of Spain. Plan de Acción de Ahorro y Eficiencia Energética 2011–2020; 2011 [accessed December 2011] http://www.idae.es/uploads/documentos/documentos_11905_PAEE_2011_2020._A2011_57bf5075.pdf.
[22] Government of the Basque Country. Estrategia Energética de Euskadi 2020 (3E2020); 2011 [accessed December 2011] http://www.euskadi.net/r33-2288/eu/contenidos/plan_programa_proyecto/plan_13/eu_plan_13/adjuntos/Estrategia%20Energ%C3%A9tica%20de%20Euskadi.pdf.
[23] Gaindegia. Atlas of the economy and society of the Basque Country; 2011 [accessed June 2011] http://www.atlasa.net/en/adierazle/eremu/18822.
[24] OTEUS Observatorio del Transporte en Euskadi. Panorámica del Transporte en Euskadi—Euskadiko Garraioaren Panoramika, 2008; 2010 [accessed June 2011] http://www.garraioak.ejgv.euskadi.net/r41-3441/es/contenidos/informe_estudio/panoramica_2008/es_def/adjuntos/Panoramica_2008_%20cas_Ab2010.pdf.
[25] Metro Bilbao. Memoria de sostenibilidad 2009; 2010 [accessed June 2011] http://www.metrobilbao.net/pdf_metro/sost09.pdf.
[26] EuskoTran, 2011 http://www.euskotren.es/es/euskotran/tranvia-bilbao [accessed June 2011].
[27] Gilbert R, Perl A. Transport revolutions: moving people and freight without oil. revised ed. London: Earthscan; 2010.
[28] Sociedad Pública de Gestión Ambiental Ihobe. Transporte y medio ambiente en la Comunidad Autónoma del País Vasco—Indicadores TMA 2007; 2006.
[29] Harvey D. Transportation and energy use. In: Harvey D, editor. Energy and the new reality. 1. Energy efficiency and the demand for energy services. London: Earthscan; 2010. p. 247–330.
[30] International Energy Agency. IEA energy statistics—2008 energy balance for Spain; 2011 [accessed June 2011] http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=ES.
[31] Intergovernmental Panel on Climate Change. Aviation and the global atmosphere. Cambridge/New York: Cambridge University Press; 1999.
[32] Comisión Nacional de la Energía. Informe sobre el sistema de garantía de origen y etiquetado de la electricidad años 2007–2008; 2009 [accessed June 2011] http://gdo.cne.es/CNE/resumenGdo.do?action=download&informe=memorias_sistema_gdo&file=Memoria+Garantias+y+Etiquetado+2007+y+2008.pdf.
[33] Ente Vasco de la Energía. Datos energéticos del País Vasco—2008; 2009 [accessed June 2011] http://www.eve.es/web/CMSPages/GetFile.aspx?guid=38d713c3-f7fa-4622-8360-20ffbb3aa50c.
[34] Sociedad Pública de Gestión Ambiental Ihobe. Inventario de emisiones de gases de efecto invernadero en la Comunidad Autónoma del País Vasco 1990–2008; 2009 [accessed June 2011] http://www.ingurumena.ejgv.euskadi.net/contenidos/inventario/inventarios_gei/es_pub/adjuntos/2008.pdf.
[35] Transport & Environment. CO_2 emissions from transport in the EU27—an analysis of 2008 data submitted to the UNFCCC; 2010 [accessed June 2011] http://www.transportenvironment.org/Publications/prep_hand_out/lid/613.
[36] International Energy Agency. IEA energy statistics—2008 energy balance for the world; 2011 [accessed June 2011] http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=29.
[37] Adams J. The social implications of hypermobility report for OECD Project on Environmentally Sustainable Transport, Paris; 1999. pp. 95–133 http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/PPC/T(99)3/FINAL/REV1&docLanguage=En.
[38] Lindstad H, Asbjørnslett BE, Strømman AH. Reductions in greenhouse gas emissions and cost by shipping at lower speeds. Energy Policy 2011, June;39(6):3456–64, doi:10.1016/j.enpol.2011.03.044. ISSN 0301-4215.
[39] Ekman CK. On the synergy between large electric vehicle fleet and high wind penetration—an analysis of the Danish case. Renewable Energy 2011, February;36(2):546–53, doi:10.1016/j.renene.2010.08.001. ISSN 0960-1481.
[40] International Transport Forum OECD/ITF. Trends in the transport sector 1970–2008; 2010.
[41] World bank statistics; 2011. http://data.worldbank.org/indicator?display=default [accessed June 2011].
[42] Giampietro M, Mayumi K. The biofuel delusion. The fallacy of large scale agro-biofuels production. London: Earthscan; 2009.
[43] Reijnders L. Conditions for the sustainability of biomass based fuel use. Energy Policy 2006;34:863–76, doi:10.1016/j.enpol.2004.09.001.